The Impact of Variable Market Price on Optimal Control of Wind-Hydro Storage System in Kenya

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Abstract—The Lake Turkana Wind Power Project (LTWP) in Northern Kenya is currently under development, scheduled to bring 300MW of wind generation online by the end of 2016. The economic issues raised by the structure of the Kenyan electricity market include a fixed feed-in tariff for the wind generators on the system, and a strict Power Purchase Agreement (PPA). This agreement appears to significantly constrain the ability of the Kenya Power Company to operate the power system in a reliable and efficient manner. This paper analyzes the impact of different price policies on the operation of the LTWP coupled with pumped hydro storage. In particular the modeling results compare the system behavior when operating under the fixed price regime versus dynamic pricing defined by use of locational marginal prices. In addition, benefits from allowing the Kenya Power Company to spill wind as needed, rather than a strict requirement to take all wind power generated are investigated. The results demonstrate that the inclusion of system-driven prices produce a significantly different operational strategy than the fixed price model. Results also show that the exclusion of dispatch flexibility in the form of wind curtailment results in increased price volatility, particularly during periods of high winds.

I. INTRODUCTION

The major goals of power system development in Kenya are increased electrification of the rural population, higher reliability in electricity provision for existing users, and reduction of reliance on diesel generation. While these goals may appear mutually exclusive, all objectives may be achieved through the increased use of renewable sources of power. In particular, there exist excellent wind resources in northern Kenya in the area of Lake Turkana. The Lake Turkana Wind Power Project (LTWP), is currently under development and will bring an additional 300MW of wind generation online by the end of 2016. Though the wind resource in the region surrounding LTWP has significant potential for the population of Kenya, the project is not without challenges. There are challenges in the management of the wind as a fuel source, in the transmission of the power to consumers and load centers, as well as economic concerns. The economic issues arise from the structure of the Kenyan electricity market, which provides a fixed feed-in tariff for the wind generators on the system. Further hampering the economic viability of this project is the structure of the Power Purchase Agreement (PPA) between Kenya Power and LTWP; all wind will be purchased at the fixed rate, regardless of forecast capabilities and system requirements. It is possible that the cost of energy will increase for the population of Kenya, while use of diesel generation for mitigating resultant variability will lead to degradation of the sustainability of the electric supply, counter to the national agenda.

In this paper, we consider the impact of pumped hydro storage and market-based pricing on wind resource utilization of the LTWP in Kenya. Kenya’s long history of reliance on hydro power ensures existence of pumped hydro capabilities, in conjunction with the expertise to operate efficiently. We specifically examine the efficacy of this approach in serving the population of the remote rural region of Marsabit. In particular, we compare the economic and system implications of replacing fixed-price PPAs with advance generation commitments and locational marginal price (LMP). The impact of these policies are examined in a stochastic dynamic programming framework, considering transmission constraints through the micro-grid structure of Marsabit [1] using the MatpowerTM software package, described in [2]. This analysis is conducted based on the assumption that the pumped hydro storage unit is owned by the wind generator
and is solely used for balancing the wind power variability, as opposed the consideration of multi-use hydro facilities, such as those considered in [3], [4], [5]. The subsequent sections of the paper are arranged as follows: in section II additional details are provided on the power system and market structure in Kenya, section III the formulation of the stochastic dynamic program (SDP) and the Marsabit microgrid are described, in Section IV the results are provided, followed by a discussion of these results in Section V.

II. KENYA POWER SYSTEM AND MARKET STRUCTURE

In many Sub-Sahara African countries, hydropower is the dominant source for electric power generation. In Kenya, as of 2011, the total installed generating capacity across all fuel types was approximately 1400 MW [6]. Hydropower accounts for approximately half of the nation’s installed generating capacity. The recurring failure of long rains in the recent past has resulted in reduced hydropower generation in the country leading to the increased use of diesel thermal plants to make up for shortfalls.

Driving the need for developing additional generating capacity is the strong load growth projected for Kenya. The Kenya Power Company forecasts average load growth from 2003 to 2023 to be 6.5% annually [7]. As part of a larger socio-economic development plan to meet the country’s growing energy needs, the Kenyan government has outlined a strategy, Vision 2030 [8], that calls for transitioning the electricity generating sector to low carbon emissions, high efficiency technologies where possible. One element of this strategy is to begin incorporating more wind power into the electricity sector, expanding from the more traditional use of wind to drive purely mechanical power loads. Currently in Kenya, wind power accounts for less than 1% of the generating capacity[9].

In the Kenyan electricity market, power is procured from the generators on the basis of negotiated PPA, which are long-term contracts of 15-20 years that define the price for each unit of power, capacity charges, and any penalties for schedule deviations [9]. In order to encourage the use of wind power, the Kenyan government is promoting a feed-in tariff policy that requires the purchase of electricity from renewable energy sources at a pre-determined price. This price is specified in the PPA, and must be sufficiently attractive to stimulate investment in renewable energy technologies. This type of policy, also traditionally popular in Europe, ensures that energy produced from renewable energy sources such as solar and wind are guaranteed a revenue stream and are thus provide an attractive return on investment [10]. The incentives provided by the feed-in tariff and the subsequent priority purchase from renewable energy sources has led to significant interest in developing wind power generation[9] .

Though Kenya is in the equatorial region, which typically does not experience a significant wind resource, specific locations within the country do have strong and persistent wind speeds throughout the year [11]. The first large wind farm to develop the nation’s wind resource will be located at Lake Turkana. The LTWP has a planned capacity of 300MW. The location of the LTWP wind farm in reference to the main grid shown in Figure 1. There are plans to install two 400kV transmission lines to connect the LTWP to the main grid. Additional wind farms are planned for development, with a projected 17% penetration by capacity into the the Kenyan power system by 2016 [6].

![Fig. 1. Kenya Transmission Grid and location of LTWP. Adapted from [8]](image-url)
For Lake Turkana, the PPA is "take-or-pay," indicating that the utility must buy all wind power that can be generated, whether or not it is used to serve load. The take-or-pay arrangement coupled with priority purchase for renewable energy has the potential to negatively impact power system and market operations [12]. Based on these concerns, World Bank withdrew its backing for the LTWP project stating that the take-or-pay provisions in the PPA would expose Kenya Power Company to large financial risk [13].

Energy storage could ease the integration of wind power by allowing limited control of the net dispatch from a wind farm. By optimally integrating a pumped hydro system with the LTWP wind farm, the energy generated could be stored during low consumption periods and the storage facility could then release energy during low wind and high consumption hours, reducing the need for wind curtailment.

This paper considers the combined operation of wind power for the Lake Turkana Wind Power wind farm with pumped hydro storage over a 24 hour operation horizon. The wind speeds used in this study are hourly wind speeds collected at Marsabit over a six-year period and are used to simulate the LTWP. The analysis in this study compares the use of the fixed price mechanism as defined by the existing PPAs and feed-in tariff structure, to a more dynamic pricing structure as defined by the use of locational marginal prices. Results also investigate the possible benefits of allowing the power system to spill wind power to benefit the system as a whole, rather than being constrained under the take-or-pay mechanism.

The model in this paper represents the Kenyan electricity supply industry structure as single buyer model with all generators selling power in bulk to Kenya Power for dispatch [14], with no bidding in a day-ahead market.

III. METHODOLOGY

The goal of this paper is the assessment of the impact of network-based LMPs in the optimal operation of a wind-hydro system in Marsabit region of Kenya. In [15], the stochastic optimal control is developed for the larger Lake Turkana Wind Project in this region with the use of fixed marginal price, as designed by the Kenya power system regulations.

The LMPs are introduced to this analysis through the inclusion of the network in the Marsabit region, detailed in III-B. The optimal decision strategy is determined by a stochastic dynamic program, described in III-A. The model is based on the following market characteristics:

- The quantity of wind power committed is constant, based on the power purchase agreement (PPA) structure in the Kenyan power system
- Wind farm operators are charged a shortfall penalty for underproduction. This penalty function is related to the diurnal pattern of system load, shown in Figure 2
- Wind energy is not curtailed, and overproduction is renumerated at a rate of half of the market price.

![Fig. 2. Penalty Function for Generation Shortfall](image)

With these market rules, a dynamic program is formulated to determine the optimal strategy for use of the pumped hydro storage unit to maximize revenue to the wind farm operator. A general overview of the formulation is given in III-A.

A. SDP for Wind-Hydro Decision Making

The advantage of coupling a wind generator with a storage system is the ability to mitigate variations over time. The inter-temporal nature of this solution also means that decisions cannot be made for the
current time without considering the possible states of the system in the future. To solve this class of optimization problem, a dynamic programming method is ideal. The general formulation is fairly standard, and is developed in detail in [16]. The general concept of the dynamic programming solution is a recursive method that determines the optimal strategy over the planning horizon, by ensuring the optimal strategy is taken at each time period to maximize additive benefits, or minimize additive costs, of decisions.

In this case, we use an open loop approach to approximate the best use of the hypothetical pumped hydro storage in conjunction with the wind farm at Lake Turkana. In this case, the state of the system at time \( k + 1 \) is determined by the relationship in (1):

\[
\begin{align*}
\text{\( s_{k+1} = f_k (s_k, u_k, w_k) \)}
\end{align*}
\]

Where \( k \) denotes the discrete time period \( (k = 1 \ldots N) \), \( s_k \) is the energy in storage at time \( k \). The decision variable, \( u_k \) is the quantity of power to charge or discharge from the storage unit, and \( w_k \) represents the random wind generation at the site. \( f_k \) is a function that describes the mechanism by which the state is updated to maximize value to the wind farm operator.

The value to the wind farm at time \( N \) is known to be the market value of stored energy, after accounting for efficiency losses, and the optimal strategy is determined by maximizing the value of the decision at each time period for all \( k \leq N \):

\[
\begin{align*}
\max_{u_k} \{ V_k (s_k) = g_k (s_k) + g_{k+1} (s_{k+1}) \}
\end{align*}
\]

For each time period, \( g_k \) is calculated as in (3) for all possible states and scenarios:

\[
\begin{align*}
g_k (s_k) = \begin{cases} 
    c_k (d_k) - p_k^c k & d_k - p_k^c \leq 0 \\
    r_k (d_k) + \gamma_k (p_k^c - d_k) & \text{otherwise}
\end{cases}
\end{align*}
\]

where \( d_k = u_k + w_k \), is the total energy delivered by the wind-hydro unit, \( p_k^c \) is the committed power, \( c_k \) is the per unit shortfall penalty, and the revenue to the wind farm per unit delivered to the grid is \( r_k \), up to \( p_k^c \) and \( \gamma_k \) for each additional unit. It is important to note that the distribution of the wind generation \( w_k \) is represented by probability weighted scenarios, so that the decision \( u_k \) is made to maximize the expected benefit over all scenarios in each time period.

The formulation described here is then implemented in Matlab\textsuperscript{TM}, with the locational marginal prices determined at each time and system state using optimal power flow capabilities of Matpower\textsuperscript{TM} and the Marsabit test system, described in III-B.

### B. Marsabit Test System

A power flow test system was developed for the village of Marsabit, Kenya [1]. The town of Marsabit is located 170 km east of the center of the East African Rift in Marsabit County, Kenya close to the Marsabit National Park and Reserve. According to the 2009 Kenya population census carried out by the Kenya Bureau of Statistics, Marsabit has a population density of 5 people per square kilometer. [17]

It is a trading and commercial center, with three gas stations, a bank, post office, and commercial area. It has one district general hospital, a mission hospital and three private health facilities. Agriculture plays a major role in the local economy, with crops and livestock produced for local consumption. For transportation, the district has limited coverage of classified roads, 62.7 km gravel surface and 37 km earth surface roads, which are impassable during the rainy season. The area is also served by Marsabit airport.

In developing the power flow test system, this information, along with satellite images from Google Earth was used to determine residential and commercial electrical demand data. Google Earth was further used to estimate distribution line distances. Data from the Kenyan Utility was used for the line parameters. [6]

The resulting power flow test system bus and branch data is shown in Table I and Table II.

A diesel generator is located at bus 1, and the wind park at bus 31, connected to Marsabit via buses 24 and 25. Diesel fuel price data is taken from DOE EIA [18], with the marginal cost for the diesel genset equal to $31.52/MWh. The existing diesel generator has a capacity of 1.056MW, sized to serve Marsabit village into the foreseeable future.

The marginal cost for wind power is set equal to $3/MWh rather than $0/MWh to acknowledge the non-zero operations and maintenance costs, while being low enough to not effect the dispatch of the generator.
diesel genset. The average diurnal load profile for Marsabit is shown in Figure 3.

Using the Marsabit test system, we consider the effect of market-based pricing in place of fixed prices in the operation of the LTWP with pumped storage. The SDP described in Section III-A is implemented in a twenty-four hour horizon, across four possible wind scenarios. The result is an optimal control strategy for the coupled system, allowing comparison of “best case” performances under various conditions and policies.

IV. RESULTS

The wind resource at LTWP is of high quality, with fairly consistent high winds. However, even the best wind resource exhibits variability and the fact that the LTWP will provide almost a quarter of the total installed capacity of the Kenya power system, means that this variability will be important to system operations. For example, in Figure 4 are four possible wind scenarios sampled from the historical data. This figure is provided to show that the wind is variable in both diurnal pattern and in absolute output level.

In order to represent the variability of wind the historical wind data for Marsabit is clustered via a k-means algorithm described in more detail in [15]. The scenarios provide a finite representation of the wind output distribution at each hour of the day, and the conditional transition probabilities between the possible states are empirically estimated under a markov assumption. The combination of the optimal power flow and the stochastic dynamic program allows the comparison of the optimal strategy for the wind farm to be compared under both the fixed and variable price regimes over the 24 hour operation horizon.

A. Comparison of Fixed Price Policy with Network-Based Prices

Figure 5 shows the difference in expected wind power delivered to the system with storage, for both the fixed price case, based on current operational practice, and the LMP case using the Marsabit test system. Depending on the available wind power, unit price of power, committed power and penalty cost, the SDP chooses the optimal decision that will maximize revenue, consequently controlling the total power delivered. Figure 5 shows the committed power, along with the delivered power (expected over all wind scenarios) for both the fixed prices and the network-based prices.
Examination of Figure 5 shows that there are differences in the use of the wind energy under the two price regimes. In the case of constant price, the optimal strategy is to always store excess power in the early hours of the day. In contrast, in the case where LMPs are determined by the dispatch of other, primarily diesel, generators in the market the optimal strategy is to deliver excess energy in some of the early hours based on revenue from LMP. The difference in storage operation under the two price regimes is highlighted in Figure 6 which shows the charge/discharge pattern of the pumped storage facility under the fixed and variable price regimes, respectively.

Figure 7, shows significant changes in storage utilization between the fixed price and network-based price policies as well, indicating that more storage capacity is desirable under the fixed price regime. This is a result of the fact that, in the fixed price case, the optimal strategy is based solely on
the penalty cost for shortfalls.

B. Impact of Wind Curtailment

An additional artifact of the Kenya feed-in-tariff policy, there is no curtailment of wind in the dispatch policy. Simulation results show that this has an adverse impact on LMPs when wind levels are high, including the existence of very volatile prices in high wind scenarios. This indicates that the strict policy against wind curtailment, though supportive of wind generators, may not be the most efficient use of the existing system resources. In Table III the statistics of the LMPs are shown and though the mean LMPs are close in value the standard deviation is significantly lower when curtailment is allowed.

The economic implications of this policy, wherein wind generators are also payed a fixed price regardless of the ability of the system to use the wind, has led to the wavering of support for the project from World Bank, as previously discussed. In this section, we consider the implications of allowing some wind curtailment in the system dispatch, up to 50% of the available wind power.

In Figure 8, the resulting energy delivered is compared between the fixed and variable price regimes, allowing wind curtailment.

Comparison of Figure 8 with Figure 5 shows that allowing wind curtailment also has an impact on the optimal strategy for use the wind and storage system. As a final comparison between the curtailment and no curtailment policies, Figure 9 shows the charge and discharge behavior of the storage facility for the case of no curtailment and 50% curtailment allowed.

Comparison of Figure 9 with Figure 6 shows that the pattern of storage and discharge changes significantly when wind curtailment is an option for the system operator.

V. CONCLUSIONS

The model developed here describes an open-loop optimal control framework for a wind-hydro system in Kenya, based on the Lake Turkana Wind Power Project, currently under development. Underlying the dynamic programming formulation is a network power flow model for the Marsabit region, providing the locational margin prices that are, in part, driving

<table>
<thead>
<tr>
<th></th>
<th>No Curtailment</th>
<th>50% Curtailment</th>
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<tbody>
<tr>
<td>Mean</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>79</td>
<td>70</td>
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TABLE III
LOCATIONAL MARGINAL PRICE STATISTICS
the operational strategy of the wind farm and storage facility. Earlier work on the optimal operational strategy was developed without a network, using fixed prices.

The results presented here show that the inclusion of system-driven prices produce a significantly different operational strategy than the fixed price model. In the fixed price model, decisions to generate or store electricity are based entirely upon the avoidance of a shortfall penalty, while the addition of price variability induces the use of the storage facility for price arbitrage as well. Results also show that the exclusion of dispatch flexibility in the form of wind curtailment results in significant price volatility, particularly during periods of high winds. At high wind penetration, the network constraints become binding, resulting in volatile system LMPs. This volatility is an important system signal that is eliminated under the fixed price PPA. If moderate wind curtailment is permitted in the dispatch decision, price volatility is reduced. Further investigation is required to assess the most efficient level of wind curtailment for system outcomes.

One of the main objectives of the LTWP is to reduce the environmental burden that electricity generation imposes on the environment due to its reliance of diesel generation. The effect of the combined wind and storage facility on carbon emissions has not been discussed here. The approach taken in this paper has the capability to provide this information, and may also be adapted to include the carbon emissions as an endogenous variable. Results addressing the emission considerations will be forthcoming. Future work will include assessing the impact of connecting the storage unit to the main grid for the benefit of the power system as a whole as well as modifying the objective of the SDP to minimize schedule deviations. Here the objective is a maximization of revenue for the wind farm operator.

It is clear that the efficacy of wind energy in assisting Kenya in achieving its national goals for sustainability and productivity is effected by the approach taken to integrating the wind into the system. The preliminary results presented here show that the existing market conditions and contractual agreements will have a significant impact on the operational decisions of the wind farm and the economic implications for the Kenya Power. While further investigation is required to identify specific
policy recommendations, the comparison of the existing and potential market structures highlights the importance of careful design in achieving renewable integration goals.

REFERENCES